

# Dimension-5 operators in a Gauge Mediated Supersymmetry Breaking Model

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## Abstract

We study the novel features in a model with Gauge Mediated Supersymmetry Breaking. If the messenger fields have positive R-parity, there will be new sources of flavor violations. We show that the dimension-5 operators will be quite important. When dressing these operators by wino-loops, the constraints on them by the present data are given.

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In models with Gauge Mediated Supersymmetry Breaking (GMSB)[1, 2], there exist the so-called “messenger fields” which transfer the information of supersymmetry (SUSY) breaking from a hidden sector to the visible sector through gauge interactions. The minimal model of this kind consists of vector-like messenger fields  $\mathbf{5} + \bar{\mathbf{5}}$  under  $SU(5)$ . Variations of the minimal model in many directions have also been studied carefully in the literature, resulting differences both in spectra and in phenomena of the Minimal Supersymmetric Standard Model(MSSM) [5, 6]. Even in the the minimal model of GMSB there can be direct interactions between the messenger fields and the matter fields. It has been noticed that the messenger fields can have either positive (Higgs-like) or negative (matter-like) R-parities[3, 4]. The former case has very rich consequences in the low energy physics.

In the present work, we will focus on the minimal model of GMSB with positive R-parity messengers. We will assume that R-parity is conserved. We will study the special features of these interactions between the messenger and the matter fields, and use the low energy data to bound the allowed couplings.

It is interesting to note that in the GMSB models, the typical masses for the messenger fields are  $M_{mess} \sim 100\text{TeV}$ . They are heavier than the squarks/sleptons and gauginos/higgsinos ( $\tilde{m} \sim 100\text{GeV} - 1\text{TeV}$ )[6], and much lighter than the color-triplet Higgs multiplets of the unification theory. Lessons on SUSY  $SU(5)$  grand unified theory[7] taught us that the dimension-5 operators are usually the dominant sources inducing nucleon decays, as they are less power suppressed by the heavy colored Higgs(ino) mass than the dimension-6 operators mediated by either gauge bosons or Higgs bosons. Furthermore, since the dimension-5 operators will be dressed by -ino (gaugino or higgsino) loops to be compared with the data, results on different flavor structures will be reached. Although these effects are suppressed by the loop factors (*e.g.*,  $1/(4\pi)^2$ ), they are compensated by the factor  $M_{mess}/\tilde{m}$  to compare with the scalar messenger mediated 4-fermion interactions which are dimension-6. Note also that the dimension-5 operators are not important in the study of R-parity violating models due to the absence of this power enhancement, while being mediated by colored Higgs which are very

heavy, they are negligibly small in the study of flavor physics in unification theories.

In the case of positive R-parity messenger fields, the superpotential between the messenger fields and the matter fields is[3]

$$\begin{aligned} W = & y_{ij} \bar{E}_i L_j L_4 + y'_{ij} \bar{D}_i Q_j L_4 + y''_{ij} \bar{U}_i Q_j \bar{L}_4 \\ & + \lambda_{ij}^l \bar{E}_i \bar{U}_j D_4 + \lambda'_{ij} L_i Q_j \bar{D}_4 + \frac{1}{2} \lambda_{ij}^q Q_i Q_j D_4 + \lambda''_{ij} \bar{U}_i \bar{D}_j \bar{D}_4. \end{aligned} \quad (1)$$

Here

$$\mathbf{5} + \bar{\mathbf{5}} = (D_4, \bar{L}_4) + (\bar{D}_4, L_4) \quad (2)$$

are the messenger superfields. They have the same quantum numbers as the  $\mathbf{5} + \bar{\mathbf{5}}$  Higgs of SU(5) theory. Bilinear terms will not be discussed here. We will not discuss the soft breaking messenger interaction either. The scalar messenger fields can induce the 4-fermion interactions between the matter fields which are dimension-6 and are proportional to  $1/M_{mess}^2$ . Consequently the low energy data will bound many of the couplings in (1)[3].

Now we focus on the dimension-5 operators which are suppressed by only  $1/M_{mess}$ . From (1) these operators can be divided into two classes. The first class of operators are relevant to the nucleon decays and are described by (see Fig. 1)

$$L_5^{(1)} = -\frac{1}{M_{D_4}} \left[ \frac{1}{2} \lambda_{ij}^q \lambda'_{lk} (Q_i Q_j) (Q_k L_l) + \lambda''_{ij} \lambda'_{lk} (\bar{U}_i \bar{D}_j) (\bar{U}_k \bar{E}_l) \right]. \quad (3)$$

This is more general than the SU(5) superpotential form [7] due to the Higgs color-triplets. Because  $\lambda_{ij}^q$  is symmetric with respect to its two indices, under the condition

$$\begin{aligned} \lambda_{ij}^q \lambda'_{lk} &= \lambda_{ik}^q \lambda'_{lj} = \lambda_{jk}^q \lambda'_{il}, \\ \lambda''_{ij} \lambda^l_{lk} &= \lambda''_{ik} \lambda^l_{lj} = \lambda''_{kj} \lambda^l_{li}, \end{aligned} \quad (4)$$

the two terms in (3) can be combined into the same superpotential form as that relevant to nucleon decays in SU(5). The second class of operators conserve both baryon number and totally lepton numbers (see Fig. 2). Due to the fact that the couplings in (1) are independent, again these interactions are written as

$$L_5^{(2)} = -\frac{\lambda'_{ij} \lambda^l_{kl}}{M_{D_4}} (L_i Q_j) (\bar{E}_k \bar{U}_l) + \frac{y_{ik} y''_{jl}}{M_{L_4}} (L_i^a \bar{E}_k) (Q_j^b \bar{U}_l)$$

$$-\frac{1}{2} \frac{\lambda_{ij}^q \lambda_{kl}''}{M_{D_4}} (Q_i Q_j)^\alpha (\bar{U}_k \bar{D}_l)^\alpha + \frac{y'_{ik} y''_{jl}}{M_{L_4}} \epsilon^{ab} (Q_i^a \bar{U}_k) (Q_j^b \bar{D}_l), \quad (5)$$

where  $a, b = 1, 2$  are flavor indices,  $\alpha = 1, 2, 3$  is color index. In (3) and (5) one fermion and one scalar are selected in each bracket, *e.g.*,

$$(Q_i Q_j)^\alpha \equiv \epsilon^{\alpha\beta\gamma} (\tilde{u}_i^\beta d_j'^\gamma - \tilde{d}_j'^\gamma u_i^\beta). \quad (6)$$

Note that the analogue superpotential of (5) in SUSY SU(5) does not violate separate lepton numbers and is negligibly small due to the suppression factor  $1/M_{H_C}$ .

Supposing that the couplings in (1) are too small to affect the spectrum of the MSSM with GMSB, they can still induce many consequences in the low energy experiments. We will assume that the leading flavor changing effects are due to charged interactions and those in (3,5). The dominant effects from these dimension-5 operators are dressed by charginos. We further simplify the discussion by taking the wino as the most important component of the charginos. We get the relevant Lagrangian

$$\begin{aligned} \mathcal{L}^{(1)} = & -\frac{1}{M_{D_4}} \frac{\alpha_2}{2\pi} \lambda'_{ij} \lambda^l_{kl} \epsilon^{\alpha\beta\gamma} \\ & \left[ (d_i'^\alpha \nu_l) (d_j'^\beta u_k^\gamma) (f(u_i, e_l) + f(u_j, d'_k)) + (u_i^\alpha e_l) (u_j^\beta d_k'^\gamma) (f(u_k, d'_j) + f(d'_i, \nu_l)) \right. \\ & \left. + (d_i'^\alpha u_k^\beta) (d_j'^\gamma \nu_l) (f(u_i, d'_k) + f(u_j, e_l)) + (u_i^\alpha d_k'^\beta) (u_j^\gamma e_l) (f(u_k, d'_i) + f(d'_j, \nu_l)) \right] \\ & + \text{h.c.} \end{aligned} \quad (7)$$

for the first class of interactions which mediate nucleon decays. All the fermions are left-handed, and we have taken  $d'$  as the interaction eigenstate while  $u$  as the mass eigenstate. Since we are using the wino-dressing diagrams, the effects of the RRRR operator in (3) are neglected. Note that the structure in (7) is different from that in the minimal SUSY SU(5), due to the fact that the color-triplet Higgs interactions do not violate flavors.

After dressed by wino, the second line in (5) results only nonleptonic 4-fermion interactions which can hardly be as important as the W-mediated interactions, while only the first line in (5) gives rise to flavor changing neutral current (FCNC) interactions. We concentrate on the FCNC interactions and get the Lagrangian

$$\mathcal{L}^{(2)} = -\frac{\alpha_2}{2\pi} \frac{y_{ik} y''_{jl}}{M_{L_4}} f(\nu_i, d_{j'}) V_{jj'} V_{j''j'}^* \bar{e}_k \frac{1-\gamma_5}{2} u_l^c \bar{u}_{j''}^c \frac{1-\gamma_5}{2} e_i + \text{h.c.} \quad (8)$$

which mediates rare and lepton number violating decays of the up-type quarks (charm quark, especially) and of the  $\tau$  lepton. Note that the  $(L \times L)$  Lorentz structure in (8) is different from the  $(L \times R)$  structure in the case of dimension-6 operators. The function  $f(f_1, f_2)$

$$f(f_1, f_2) \equiv \frac{m_{\tilde{w}}}{m_{\tilde{f}_1}^2 - m_{\tilde{f}_2}^2} \left( \frac{m_{\tilde{f}_1}^2}{m_{\tilde{f}_1}^2 - m_{\tilde{w}}^2} \ln \frac{m_{\tilde{f}_1}^2}{m_{\tilde{w}}^2} - \frac{m_{\tilde{f}_2}^2}{m_{\tilde{f}_2}^2 - m_{\tilde{w}}^2} \ln \frac{m_{\tilde{f}_2}^2}{m_{\tilde{w}}^2} \right) \quad (9)$$

is the standard triangle loop function.

We now use (7) and (8) to bound the couplings in (1). We take the typically values

$$M_{\tilde{w}} = 500\text{GeV}, \quad M_{\tilde{f}} = 800\text{GeV}, \quad M_{D_4} = M_{L_4} = 100\text{TeV} \quad (10)$$

and  $\alpha_2(m_Z) = 0.0335$  in our numerical estimation. First we consider nucleon decays. We use the  $\tau(N \rightarrow \nu K) > 0.86 \times 10^{32}\text{years}$  [8] to get

$$|\lambda_{12}^q \lambda'_{l1}| < 3.7 \times 10^{-21} \left( \frac{M_{D_4}}{100\text{TeV}} \right) \quad (l = 1, 2, 3), \quad (11)$$

which is of the same order as the bounds on the other products of couplings in (1) (*e.g.*,  $\lambda' \lambda'' < 10^{-21}$  in [3]).

In the FCNC processes induced by the dimension-5 operators, the appearance of  $V_{j'j} V_{j''j'}^*$  in (8) indicates the GIM cancellations among down-type squarks in the loops of Fig. 3. Consequently, most of the results depend strongly on the details of the model and the parameters which will not be discussed. However, processes with  $j'' = j$  will not suffer the GIM mechanism and we get

$$\begin{aligned} y_{31(13)} y''_{11} &< 0.064 \left( \frac{M_{L_4}}{100\text{TeV}} \right) && \text{from } Br(\tau \rightarrow e\pi^0) < 2.2 \times 10^{-6}, \\ y_{32(23)} y''_{11} &< 0.066 \left( \frac{M_{L_4}}{100\text{TeV}} \right) && \text{from } Br(\tau \rightarrow \mu\pi^0) < 8.2 \times 10^{-6}, \\ y_{11} y''_{12(21)} &< 0.35 \left( \frac{M_{L_4}}{100\text{TeV}} \right) && \text{from } Br(D^+ \rightarrow \pi^+ e^+ e^-) < 8.8 \times 10^{-6}, \\ y_{12(21)} y''_{12(21)} &< 0.21 \left( \frac{M_{L_4}}{100\text{TeV}} \right) && \text{from } Br(D^+ \rightarrow \pi^+ e^\pm \mu^\mp) < 3.4 \times 10^{-5}, \\ y_{22} y''_{12(21)} &< 0.15 \left( \frac{M_{L_4}}{100\text{TeV}} \right) && \text{from } Br(D^+ \rightarrow \pi^+ \mu^+ \mu^-) < 5.2 \times 10^{-5}. \end{aligned} \quad (12)$$

Here very simple estimations on hadronic matrix elements have been used based on chiral perturbation theory[9]. It is interesting that the bounds on  $yy''$  are absent if

the dimension-6 operators are studied. The bounds in (12) are also comparable in size with the bounds on  $yy, y''y''$  given in the dimension-6 case[3].

We have studied the effects of novel dimension-5 operators in the minimal GMSB model with direct messenger-matter interactions. We find that these effects are comparable with the dimension-6 operators. Although we have limited in discussing the minimal GMSB model, our results can be easily extended to other SUSY models with extra chiral multiplets: if they are not too heavy, the dimension-5 operators have important effects in the low energy phenomena.

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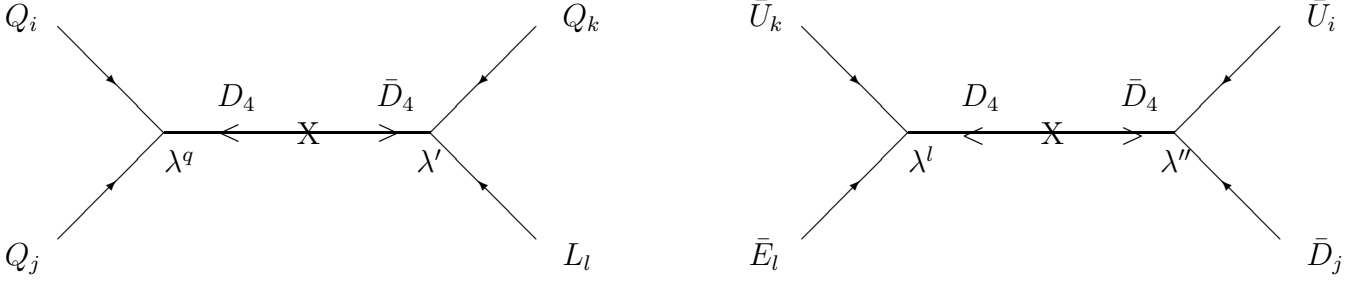


Figure 1: Dimension-5 operators which are relevant to nucleon decays.

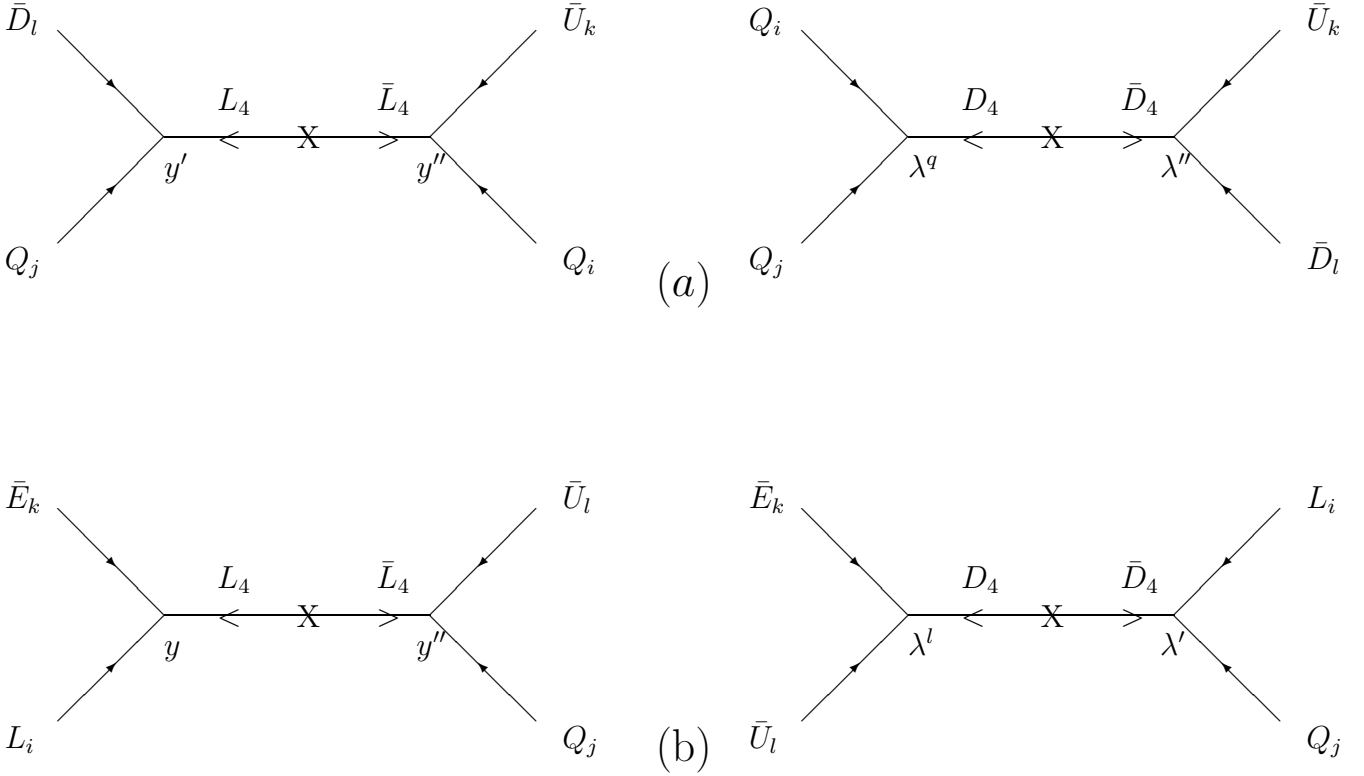


Figure 2: Dimension-5 operators which conserve baryon number. (b) contains FCNC interactions. For  $i \neq k$  (b) also violates lepton number.



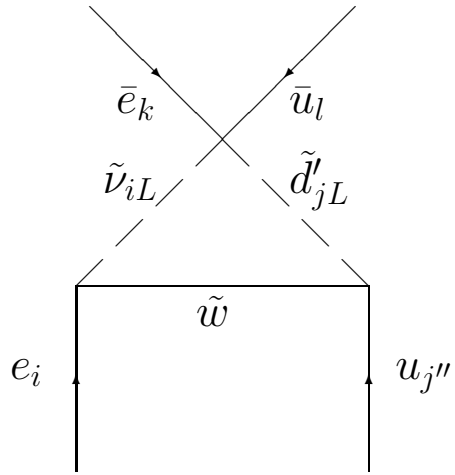


Figure 3: Dimension-5 operators dressed by wino which mediate FCNC processes of up-type quarks.